The Evolving ISM in the Milky Way & Nearby Galaxies

Planetary Nebulae: Exposing the Top Polluters of the ISM

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ABSTRACT

The high mass loss rates of stars in their asymptotic giant branch (AGB) stage of evolution is one of the most important pathways for mass return from stars to the ISM. In the planetary nebulae (PNe) phase, the ejected material is illuminated and can be altered by the UV radiation from the central star. PNe therefore play a significant role in the ISM recycling process and in changing the environment around them.

We show some highlights of the results of observations that have been carried out using the Spitzer instruments to study the gas and dust emission from PNe in the Milky Way and nearby galaxies. Spitzer is especially sensitive to the cool dust and molecules in the PNe shell and halos. We present new results from our program on Galactic PNe, including IRAC and IRS observations of NGC 6720 in the ring and halo of that nebula.

Subject headings: galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction — ISM: structure

1. Introduction

A key link in the recycling of material to the Interstellar Medium (ISM) is the phase of stellar evolution from Asymptotic Giant Branch (AGB) to white dwarf star. When stars are on the AGB, they begin to lose mass at a prodigious rate. The stars on the AGB are relatively cool, and their atmospheres are a fertile environment for the formation of dust and molecules. The material can include molecular hydrogen (H_2), silicates, and carbon-rich

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dust. The star is fouling its immediate neighborhood with these noxious emissions. The star is burning clean hydrogen fuel, but unlike a "green" hydrogen vehicle that outputs nothing except water, the star produces ejecta of various types, some of which have properties similar to that of soot from a gas-burning automobile (Allamandola et al. 1985). A significant fraction of the material returned to the ISM goes through the AGB - PNe pathway (Kwok 2000), making these stars one of the major sources of pollution of the ISM.

However, these stars are not done with their stellar ejecta yet. Before the slow, massive AGB wind can escape, the star begins a rapid evolution where it contracts and its surface temperature increases. The star starts ejecting a less massive but high velocity wind that crashes into the existing circumstellar material, which can create a shock and a higher density shell. As the stellar temperature increases, the UV flux increases and it ionizes the gas surrounding the central star, and can excite emission from molecules, heat the dust, and even begin to break apart the molecules and dust grains. The objects are then visible as planetary nebulae, exposing their long history of spewing material into the ISM, and further processing the ejecta. There are even reports that the central stars of some PNe may be engaging in nucleosynthesis for purposes of self-enrichment (e.g., Dinerstein et al. 2003), which can be traced by monitoring the elemental abundances in the nebulae. Clearly, we must assess and understand the processes going on in these objects in order to understand their impact on the ISM, and their influence on future generations of stars.

We present here results primarily from the IRAC GTO study of PNe. See reviews by Bernard-Salas et al. (2005, 2006) for summaries of the IRS observations of PNe, and Hora (2006a, 2006c, 2008a) for a review of IRAC, MIPS, and IRS results.

2. IRAC Imaging of Planetary Nebulae

The IRAC camera (Fazio et al. 2004) was used to obtain images of each of the PNe at 3.6, 4.5, 5.8, and 8.0 μm. For the GTO program on Galactic PNe (PID 68), 5-10 images per position using 30 sec HDR frames were obtained. A total of 52 PNe were observed in the survey. More details on the data reduction steps and some initial results were presented in Hora et al. (2004, 2006a, 2006b). The IRAC images show that Spitzer can probe the faint extended emission from ionized gas, warm dust, PAHs, and H_2. The appearance of the extended emission in the IRAC bands is similar to the optical appearance in some cases, but often there are important differences. For example, in NGC 246 an unexpected "ring" of emission is prominent in the longer IRAC wavelengths within the elliptical shell of the nebula. In PNe that are dominated by H_2 emission, such as in NGC 6720, NGC 6853, and NGC 7293, the spatial distribution closely matches that of the 2.12 μm H_2 line emission. Because the

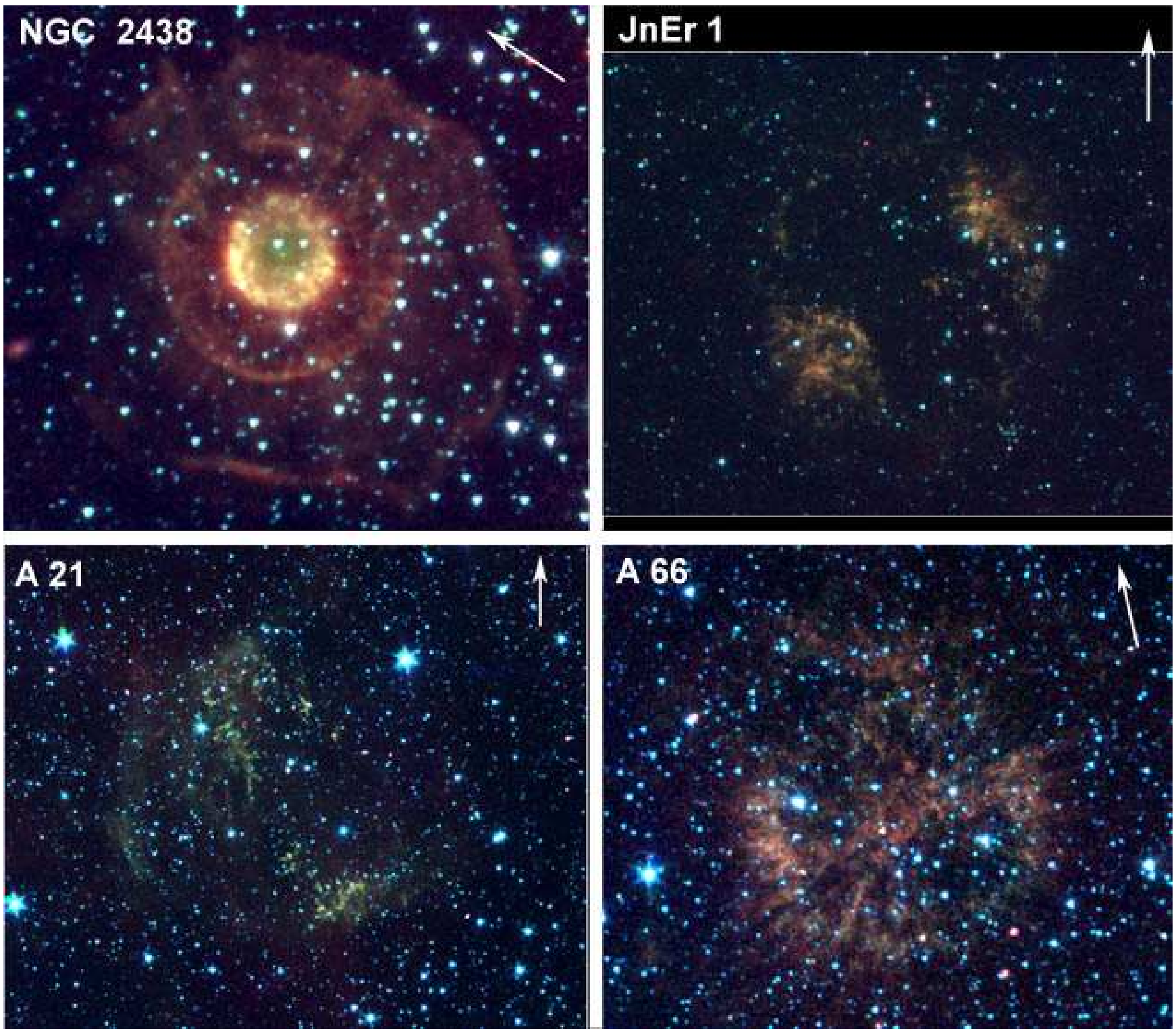

Fig. 1.— Examples of PNe NGC 2438, JnEr 1, A 21, and A 66 from the IRAC GTO survey. The width of the images is approximately 5.5′, 9′, 14′, and 7′, respectively. North is indicated by the direction of the arrow in the images. The IRAC 3.6, 4.5, and 8.0 μm bands are shown as blue, green, and red, respectively.

stellar emission and scattered light and nebular free-free continuum is much reduced at the IRAC wavelengths, the emission from the halo and from the dust and molecular lines appear more prominent.

Some new images of four PNe in the survey are shown in Figure 1. The PN NGC 2438 appears similar to NGC 6720, with an inner bright ring of emission, and two red outer shells, with "spokes" or filaments extending radially outward from the center. In JnEr 1, the brightest part of the nebula is in the equatorial region of the bipolar lobes, and is very clumpy and consistent with the morphology observed in the 2.12 μm H_2 line. In A 21, the emission is diffuse and similar to optical Hα images. In A 66, the brightest emission is in the same region as in optical images, but much more clumpy and filamentary. There is also a faint halo that extends to roughly twice the diameter of the optical ring. These PNe exhibit the general characteristics of the IRAC sample – there is often correspondence to the optical images, likely due to forbidden line emission in the IRAC bands from the ionized gas. Except for young PNe such as NGC 7027, there does not seem to be significant continuum emission from warm dust in the 3 - 8 μm spectral range, or any spatially distinct unidentified infrared (UIR) feature emission (which is usually associated with polycyclic aromatic hydrocarbons – PAH). In many PNe, emission from H_2 often dominates in the outer regions of the nebulae and the halos, making them relatively bright at the longer wavelengths.

An example of an object for which we have IRAC images and IRS spectra is NGC 6720. The IRAC image is shown in Figure 2, with the IRS slit positions superposed. The IRS low resolution spectra are shown in Figure 3. In the spectrum obtained on the main bright ring, the dominant emission is from the [Ar III], [S IV], and [Ne II] lines from the ionized gas. However, in both spectra we see the pure rotational lines of H_2, similar to what is seen in NGC 7293 (Hora et al. 2006b), and in the halo these are the dominant emission feature. In the Ring spectrum, there is some evidence for a weak broad feature near 11.3μm which could be UIR feature emission. The corresponding features at 7.7 and 8.6 μm are in the overlap between the IRS orders, and have several other features near those wavelengths, so the evidence there is not as clear.

3. IRAC colors of PNe

Data on the Large Magellanic Cloud (LMC) PNe were obtained as part of the SAGE Legacy survey (Meixner et al. 2006) and used 4×12 sec HDR frames. The IRAC magnitudes of a set of previously known PNe in the LMC were extracted from the SAGE data. The IRAC [3.6] – [4.5] vs [4.5] – [8.0] colors of the PNe detected in all four IRAC bands are shown in Figure 4 (Hora et al. 2008b). A subset of Galactic PNe from the GTO survey and Kwok

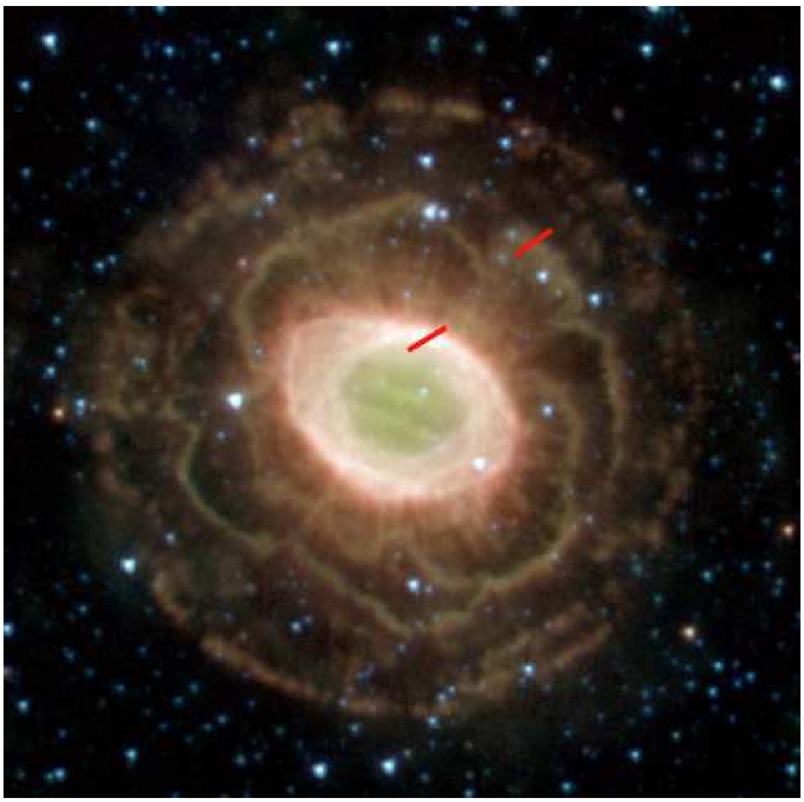

Fig. 2.— The IRAC 3-color image of NGC 6720, with 3.6, 4.5, and 8.0 μm images as red, green, and blue, respectively. North is up, and the image is $5'$ in size. The slit positions of the spectra shown in Figure 3 are shown as red boxes.

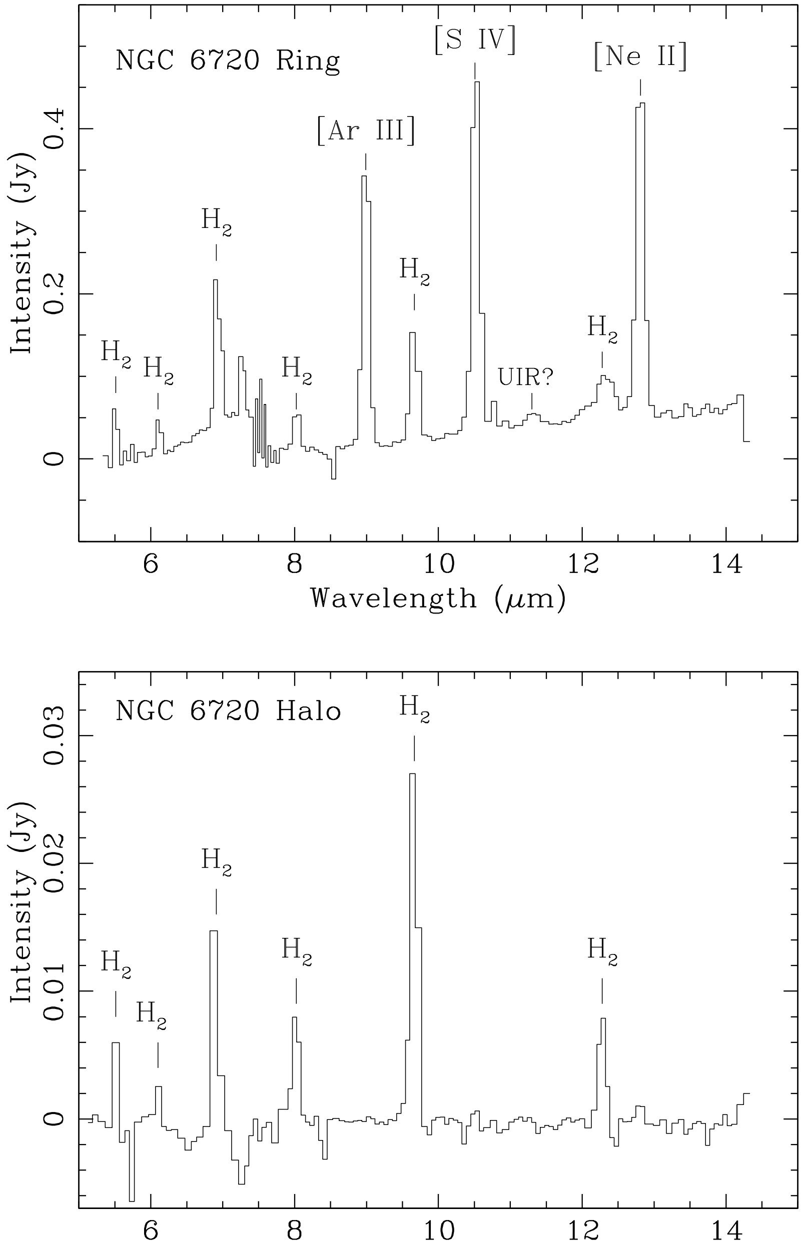

Fig. 3.— The IRS low-resolution spectra of two locations in NGC 6720. The upper spectrum was taken at a location in the main bright ring of the nebula, and the lower spectrum at a position in the fainter outer halo, as indicated in Figure 2. Both locations show strong emission from H_2. The "Ring" spectrum shows forbidden line emission from [Ar III], [S IV], and [Ne II] in the ionized gas, and possibly weak unidentified infrared (UIR) emission at 11.3 μm.

et al. (2008) study of the PNe in GLIMPSE are shown as green stars, the LMC PNe are the red triangles (some of their names are labeled in blue), and the SAGE LMC point sources are the black dots. The PNe are mostly in the 0.5 – 1.2 range of [3.6] – [4.5] color, and in the 1 – 4 range of [4.5] – [8.0] color. The PNe that exhibit strong PAH and/or warm dust continuum are on the right side of the plot (larger [4.5] – [8.0] color), as one might expect, and have [3.6] – [4.5] colors closer to 1. Strong forbidden line emission in the 8.0 μm band also results in objects appearing on the right side of the plot. However, the objects with no continuum dust emission have lower [3.6] – [4.5] values. The PNe with strong forbidden line emission and no PAH or dust continuum emission, for example SMP 83, are on the left side of the plot. The Galactic and LMC PNe have similar distributions.

4. Summary

The Spitzer instruments, with their unmatched sensitivity, have given us new tools to detect and characterize the stellar ejecta that the central stars of PNe have illuminated. Not only will this lead to a better understanding of PNe, but will allow us to determine the properties of the material that is being returned to the ISM. We will then be better able to assess the full impact of these objects on their neighbors and their surrounding environment.

This work is based on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory (JPL), California Institute of Technology under NASA contract 1407. Support for this work was provided by NASA and through JPL Contract 1256790.

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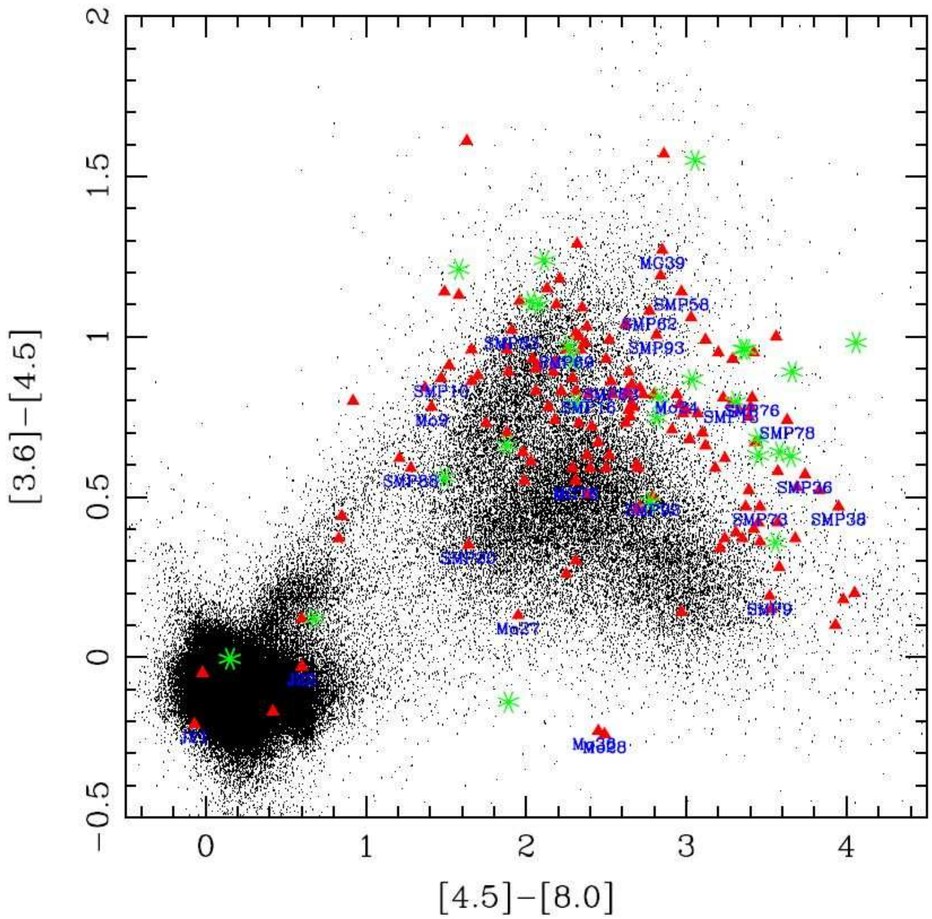

Fig. 4.— The LMC PNe sample (red triangles; some source names labeled in blue) compared to Galactic PNe (green asterisks), from Hora et al. (2008b) and Kwok et al. (2008). The black points are all other point sources in the SAGE catalog (Meixner et al. 2006).

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